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EARTH-JUPITER-EARTH TRAJECTORIES AND THE EUROPA ICE-CLIPPER MISSION *

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The nature of optimized Earth-Jupiter-Earth trajectories is described in a search for a Europa Flyby that could return a gaseous sample from close proximity to Europa. Flights from four to ten years duration are considered. Long flight times are required in order to go around Jupiter in the same direction as Europa and ten-year flights are needed to be able to approach Europa.

Trajectories are shown for launches in 2000, 2001, and 2003 that make use of two-year delta-V Earth gravity assists in order to avoid the high C3'S required for direct launches to Jupiter. Total flight times are thus twelve years. Close approach to an asteroid can be obtained on each leg of these trajectories at an average cost of about 50 m/s delta-V.

EARTH-JUPITER-EARTH TRAJECTORIES

The basic problem proposed for this paper was to find trajectories that fly through the Jupiter system for the purpose of gaseous sample collection and returning it to Earth. The returning sample is to be captured at Earth by aerobraking in the atmosphere. This scenario involves both minimum launch energy and minimum return speed. Thus the outbound and return trajectories will be nearly images of each other in the Sun-Jupiter line and also not far from 180 degree transfer. Figures 1 and 2, which show four-year and ten-year trajectories respectively, illustrate the two types of trajectories that satisfy these requirements and properties.

With either of these trajectory types the spacecraft appears from the point of view of Jupiter to be coming toward Jupiter from the leading direction, that is to say Jupiter passes it as both go around the Sun. If going outward the trajectory is bent to go inward, Figure 1. If going inward the trajectory is bent outward, Figure 2.

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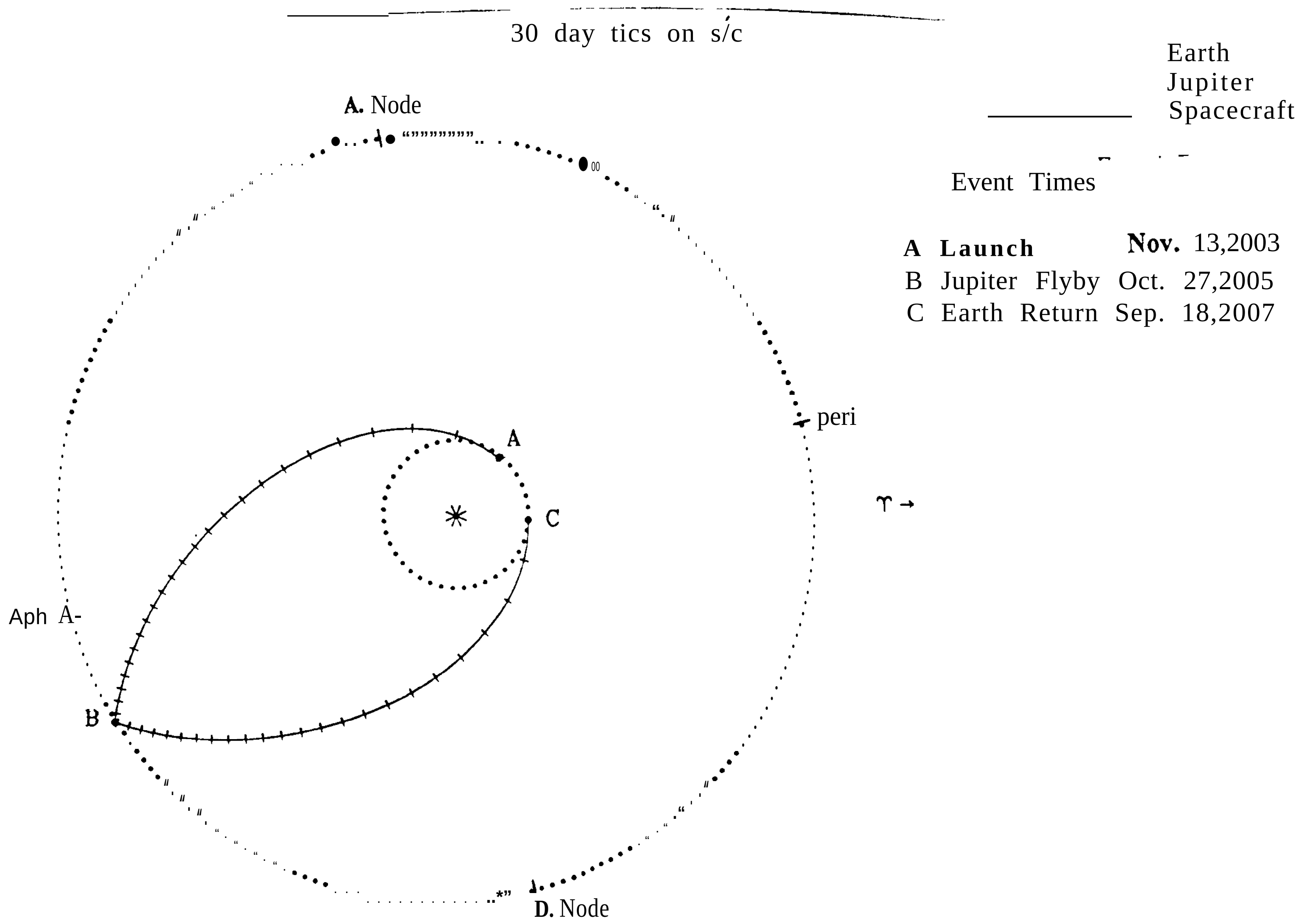

Figure 1 Earth–Jupiter– Earth 2003 4 years

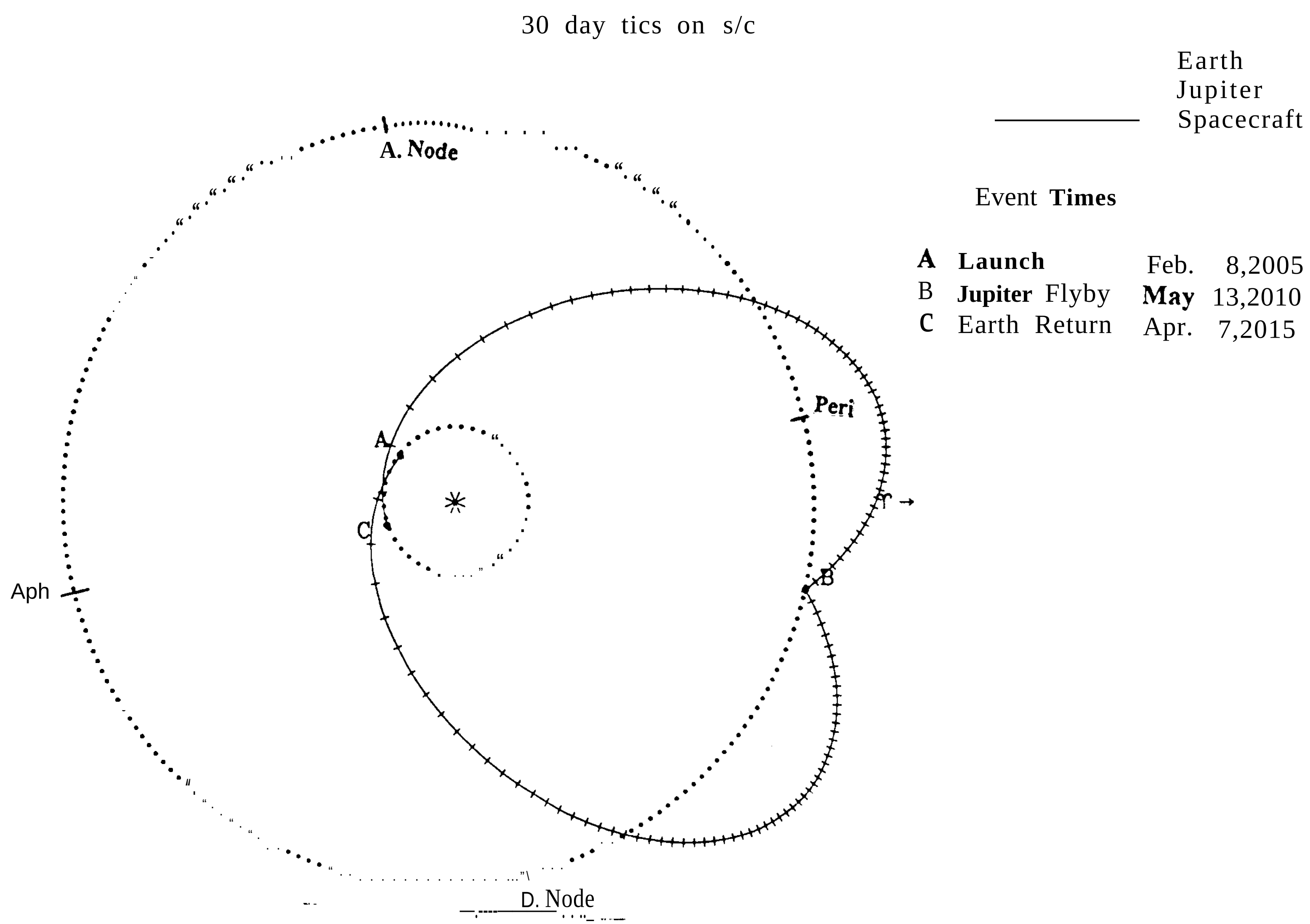

Figure 2 Earth–Jupiter–Earth 2005 10 years

Trajectory data on type 1 four-year trajectories **is given in** Table I which includes launch information, Jupiter flyby information, and the Earth return speed. The precise flight time in indicated in the Delta-t column which is the difference in days between the flight time and precisely four years. The negative value means that these are all type 1 trajectories(less than 180 degree central angle, both outbound and returning. Tables 2, 3, and 4 refer to the type two trajectories for 8, 9, and 10 year respectively. For these all the Delta-t values are positive and all the trajectories are of type 2. In these tables there are presented the data for thirteen successive Jupiter launch opportunities. The purpose is to show the variations of these trajectories over a fill cycle of eleven Jupiter opportunities in 12 years, and to show that any trajectory will repeat approximately in 12, 24, 36,.. years.

Three, five, six, and seven year Earth-Jupiter-Earth trajectories are all possible, but no data is included here. Three year flight require so much bending at Jupiter that some would have to have pereijove distances below the radius of Jupiter. Five and six year returns are possible but all will require little bending at Jupiter. They will flyby Jupiter at such very large distances that it is doubtful a two body analysis would be close the real solution. Seven year flights have perijove distances from 31.5 to 78 Jupiter radii, and thus could not reach the Galilean satellites (see Table 5).

Which of these two types of trajectories is to be used is determined by the operation to be undertaken while flying through the Jupiter system. Thus a description of the Jupiter system is included as Table 5 which gives the orbital and physical properties of the four Galilean moons. On the short four-year trajectories the flight near Jupiter is in the opposite direction to that of the Galilean moons, so with respect to them the relative velocity will be very high, 34 km/s for Europa for example. In addition the flybys would be in the dark, that is opposite the Sun as seen from Jupiter. Thus one is forced to consider a long trajectory for a mission to observe any of these moons, and now a study of the perijove distances becomes essential. The perijove distances for all four trajectory times are shown in Figures 3 and 4. Thus it is seen that Europa, whose orbit varies from 9.30 to 9.48 Jupiter radii can only be reached with ten year trajectories launched from 2000 through 2009 (plus any multiple of 12).

Table 7

THE GALILEAN MOONS OF JUPITER

NAME	RADIUS km	G times MAss km3/sec2	ORBITAL PERIOD days	SEMI-W AXIS RJ'S	ORBITAL SPEED km/ sec
Io	1821	5934	1.769	5.90	17.33
Europa	1565	3196	3.551	9.47	13.74
Ganymede	2634	9885	7.154	14.97	10.88
Callisto	2403	7172	16.689	26.34	8.25

Table 1
FOUR YEAR EARTH-JUPITER-EARTH TRAJECTORIES

Table 1.			FOUR YEAR EARTH-JUPITER-EARTH TRAJECTORIES						
Launch Year	Mon-Day	Perijove RJ's	C3 km2/s2	dla deg.	time @ Jup days	V-inf Jup. km/s	Bend Angle deg	delta t days	V-inf,Ear. km/s
2000	Aug. 7	14.51	88.1	26.0	685	7.57	86.4	-35	9.28
2001	Sep. 11	11.06	91.6	33.3	690	7.76	92.6	-41	9.58
2002	Oct. 16	9.53	93.2	35.6	700	7.93	96.8	-50	9.65
2003	Nov. 14	9.70	90.9	29.4	714	7.93	96.2	-56	9.90
2004-5	Dec. 12	11.68	85.7	15.3	729	7.75	91.6	-41	9.41
2006	Jan. 9	15.49	80.2	-4.9	739	7.51	84.1	-41	9.20
2007	Feb. 12	22.40	79.5	-28.3	738	7.30	75.5	-41	9.14
2008	Mar. 20	26.60	82.5	-38.0	725	7.18	68.7	-51	9.86
2009	Apr. 27	28.10	84.6	-35.5	708	7.12	67.4	-41	9.28
2010	Jun. 2	24.80	85	-19.7	692	7.16	71.3	-41	9.25
2011	Jul. 8	18.90	85.7	2.2	694	7.32	79.1	-41	9.19
2012	Aug. 12	13.80	88.6	27.4	685	7.56	87.7	-41	9.28
2013	Sep. 16	10.70	92	34.3	692	7.80	94	-41	9.59

Table 2
EIGHT YEAR EARTH-JUPITER-EARTH TRAJECTORIES

Table 2.			EIGHT YEAR EARTH-JUPITER-EARTH TRAJECTORIES						
Launch Year	Mon-Day	Perijove RJ's	C3 km2/s2	dla deg.	time @ Jup days	V-inf Jup. km/s	Bend Angle deg	delta t days	V-inf,Ear. km/s
2000	Aug. 31	31.30	90.4	6.83	1459	6.50	69.9	40	9.61
2001	Sep. 28	30.75	92.9	10.63	1521	6.55	70	52	9.67
2002	Nov. 9	27.53	84.7	5.65	1558	6.75	71.8	35	9.14
2003-4	Dec. 14	22.92	81.1	3.22	1579	7.08	74.8	30	8.86
2005	Jan. 13	18.94	81.9	-1.35	1571	7.44	77.9	35	8.98
2006	Feb. 16	16.63	82.9	-7.74	1599	7.68	80.2	48	9.30
2007	Mar. 16	16.08	85.8	-7.35	1522	7.74	80.8	55	9.26
2008	Apr. 18	17.16	85.2	-5.16	1476	7.59	79.9	40	9.30
2009	May. 26	20.02	81.8	-1.78	1380	7.28	77.5	38	9.26
2010	Jul. 2	24.42	83.4	-0.74	1379	6.91	74.3	30	9.26
2011	Aug. 3	28.81	88.2	3.84	1416	6.63	71.4	30	9.60
2012	Sep. 5	31.48	90.4	7.01	1466	6.50	69.8	40	9.62
2013	Oct. 10	30.66	88.2	7.55	1517	6.55	70.1	35	9.41

Table 3
NINE YEAR EARTH-JUPITER-EARTH TRAJECTORIES

Table 3.			NINE YEAR EARTH-JUPITER-EARTH TRAJECTORIES						
Launch Year	Mon-Day	Perijove RJ's	C3 km2/s2	dla deg.	time @ Jup days	V-inf Jup. km/s	Bend Angle deg	delta t days	V-inf,Ear. km/s
2000	Oct. 2	17.14	89.6	10.9	1679	7.14	84.2	40	9.56
2001	Oct. 21	16.10	88.1	9.1	1742	7.29	84.8	43	9.34
2002	Nov. 25	14.16	84.7	6.5	1783	7.59	86.5	35	9.06
2003-4	Dec. 18	12.07	83.9	1.6	1791	7.97	88.6	33	9.26
2005	Jan. 21	10.61	85.2	-4.4	1774	8.26	90.5	33	9.20
2006	Feb. 27	9.92	85.8	-9.7	1694	8.42	81.5	30	9.61
2007	Mar. 30	16.05	85.7	-10.9	1622	8.36	91.5	43	9.57
2008	May. 5	16.94	85.5	-6.5	1563	8.14	90.5	43	9.44
2009	Jun. 7	12.82	84.4	-3.2	1538	7.79	88.6	33	9.40
2010	Jul. 13	14.80	86.9	4.1	1556	7.44	86.4	23	9.59
2011	Aug. 19	16.61	89.6	7.9	1611	7.19	84.7	33	9.59
2012	Sep. 21	17.09	89.6	10.9	1687	7.16	84.2	33	9.55
2013	Oct. 26	15.93	87.5	8.9	1748	7.32	85	28	9.30

Table 4
TEN YEAR EARTH-JUPITER-EARTH TRAJECTORIES

Table 4.			TEN YEAR EARTH-JUPITER-EARTH TRAJECTORIES						
Launch. Year	Men-Day	Perijove RJ's	C3 km2/s2	dla deg.	time @ Jup days	V-inf Jup. km/s	Bend Angle deg	delta t days	V-inf,Ear. km/s
2000	Oct. 4	10.88	91.5	11.10	1905	7.79	94.2	45	9.50
2001	Nov. 7	9.76	88.4	9.70	1976	8.04	95	45	9.22
2002	Dec. 12	8.58	88.6	5.06	2110	8.40	96.4	40	9.17
2003-4	Jan. 12	7.58	88.9	-1.50	1981	8.74	97.9	48	9.20
2005	Feb. 9	6.97	88	-7.34	1920	8.96	99	58	9.44
2008	Mar. 11	6.83	88.4	-10.57	1890	9.03	94.3	50	9.53
2007	Apr. 11	7.10	88	-9.92	1761	8.88	99	50	9.57
2008	May.15	7.80	86.7	-6.94	1708	8.60	98	50	9.55
2009	Jun. 20	8.88	87.1	-7.53	1700	8.24	96.6	50	9.60
2010	Jul. 26	10.07	90.3	3.74	1743	7.91	95.1	40	9.69
2011	Aug. 31	10.77	92.4	9.37	1827	7.75	94.2	50	9.68
2012	Oct. 7	10.58	91.1	11.13	1920	7.82	94.3	50	9.55
2013	Nov. 11	9.81	88.1	9.20	1982	8.09	95.2	40	9.24

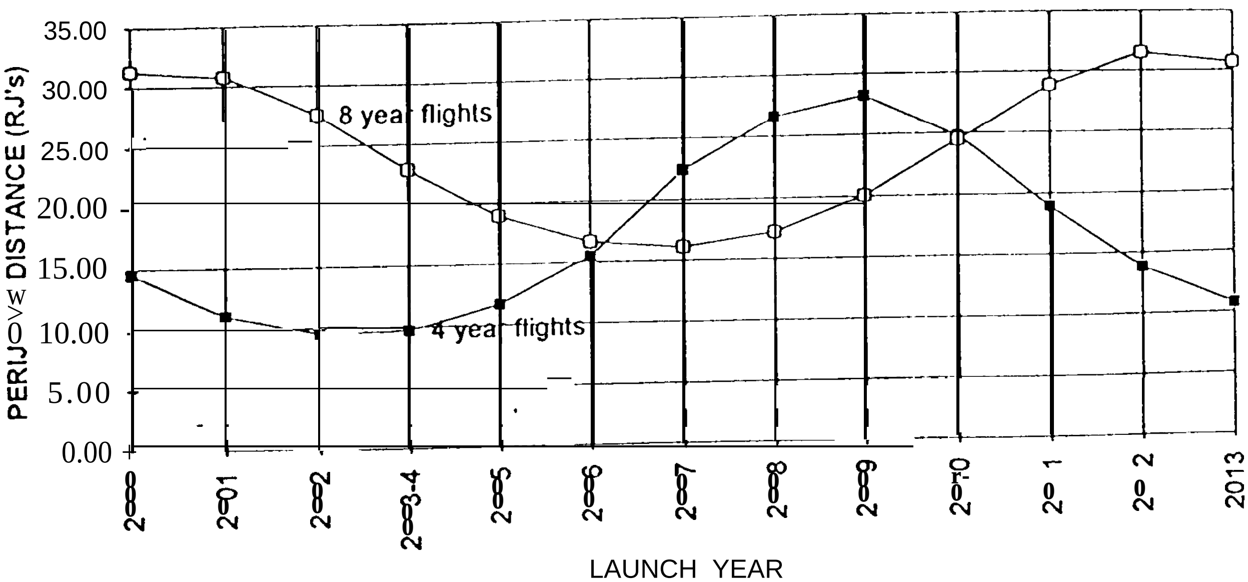

Figure 3 Earth-Jupiter-Earth Trajectories, Four Years and Eight Yearn

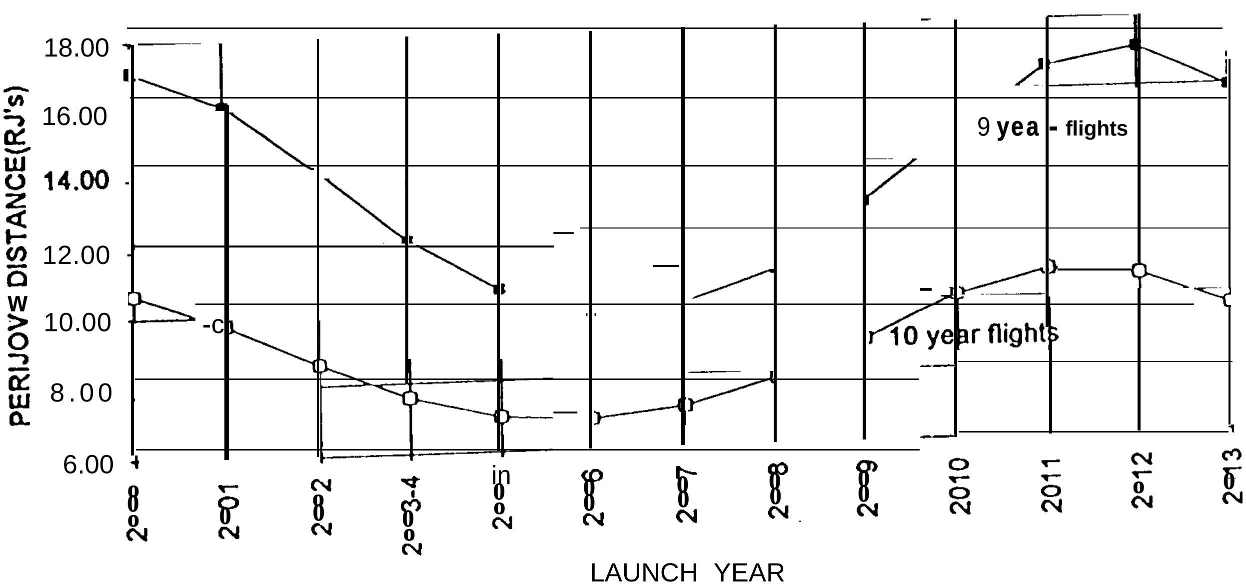

Figure 4 Earth-Jupiter-Earth Trajectories, Nine Tears and Ten Yearn

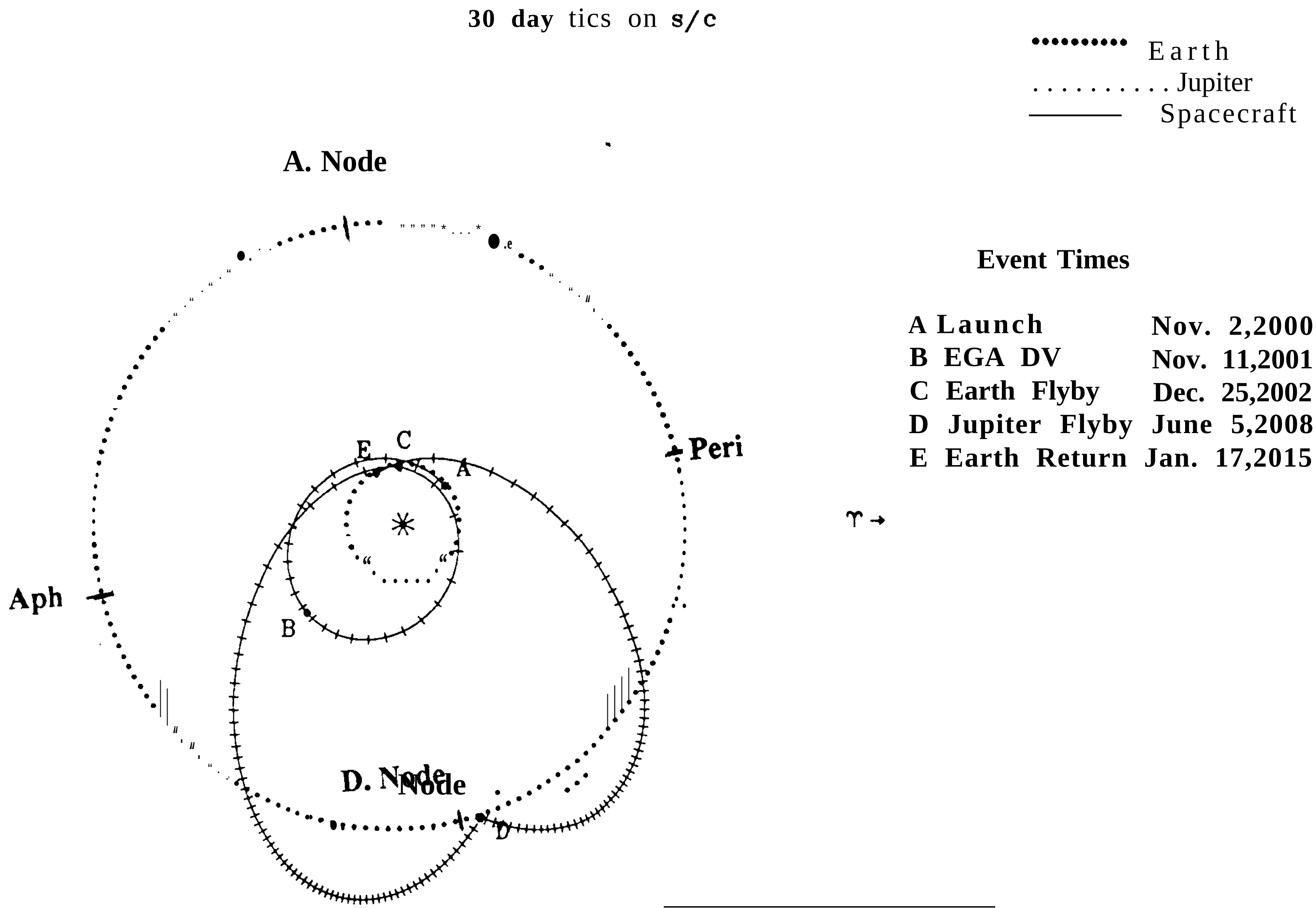

Figure 5 Europa Ice-Clipper Trajectory, 2000 Launch

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Table 6 !		TRAJECTORY DATA SUMMARY FOR THE EUROPA ICE-CLIPPER MISSION									
		November 2000 Launch Using Two-year DVEGA									
B plane	Launch En	Decl.	Total	DVEGA	JOX*	EUROPA	************	EUROPA	FLYBY	************	'-*"	Earth Re !
Angle	C3	Lau.Az,	pL D V =	(DV +	DV +	Tar. DV)	Latitude	Longitude	FI.P.Azim.	Speed	JO Tru An.	V-inf
(deg)	(km2/s2)	(deg)	(mls)	(m/s)	(m/s)	(m/s)	(deg)	(deg)	(deg)	(km/s) .	(deg)	(km/s)
83	28.2	16.4	686	671	0	15	-79.1	202.5	26.7	8.99	26.8	9.32
80	28.2	16.4	697	671	o	26	-77.3	191.9	38.5	8.90	25.7	9.32
75	28.2	16.4	729	672	0	57	-73.5	181.1	51.1	8.75	23.8	9.32
70	28,2	16.4	761	671	0	89	-69.1	175.6	58.6	8.60	21.9	9.32
65	28.2	16.4	792	672	0	120	-64.5	172.9	63.3	8.47	20.1	9.32
60	28.2	16.4	822	672	O	150	-59.8	171.6	66.5	8.35	18.3	9.32
		December 2001 Launch Using Two-year DVEGA										
88.6	28.4	4.85	834	745	70	20	-82.5	208.5	0.4	11.16	45.9	9.26
80	28.3	5.31	854	739	102	13	-78.4	161.7	48	10.79	44.3	9.26
75	28.2	5.52	874	727	114	33	-74.2	150.8	59.6	10.65	43.1	9.26
70	28.1	5.73	896	717	128	50	-69.7	144.9	66.1	10.52	42	9.26
65	28.1	5.93	919	709	145	65	-65	141.6	70.1	10.57	40.9	9.26
60	28	6.13	942	701	162	79	-60.2	139.6	72.9	10.45	39.8	9.26
55			965.2	717.1	238.1	0						
	28.0	6.46	975.1	711.7	263.3	0	-50.9	136.1	76.2	10.33	39.9	9.18
		January 2003 Launch Using Two-year DVEGA										
90	28.2	-4.2	988	788	162	39	-85.1	200.9	0.4	12.42	55.1	9.47
'80	28.3	-3.9	998	786	187	25	-79.1	139.1	62.9	12.25	53.7	9.47
70	28.4	-3.6	1027	785	233	10	-69.6	127.3	75.2	12.08	52.4	9.47
60	28.5	-4.3	1069	782	287	0	-59.8	123.5	79.4	11.92	51.2	9.47

* JOX = Near Jupiter Orbit crossing -Outbound

All Trajectories Have Earth Flyby at 300 km. Altitude

All Trajectroies Have Europa Flyby at 50 km Altitude

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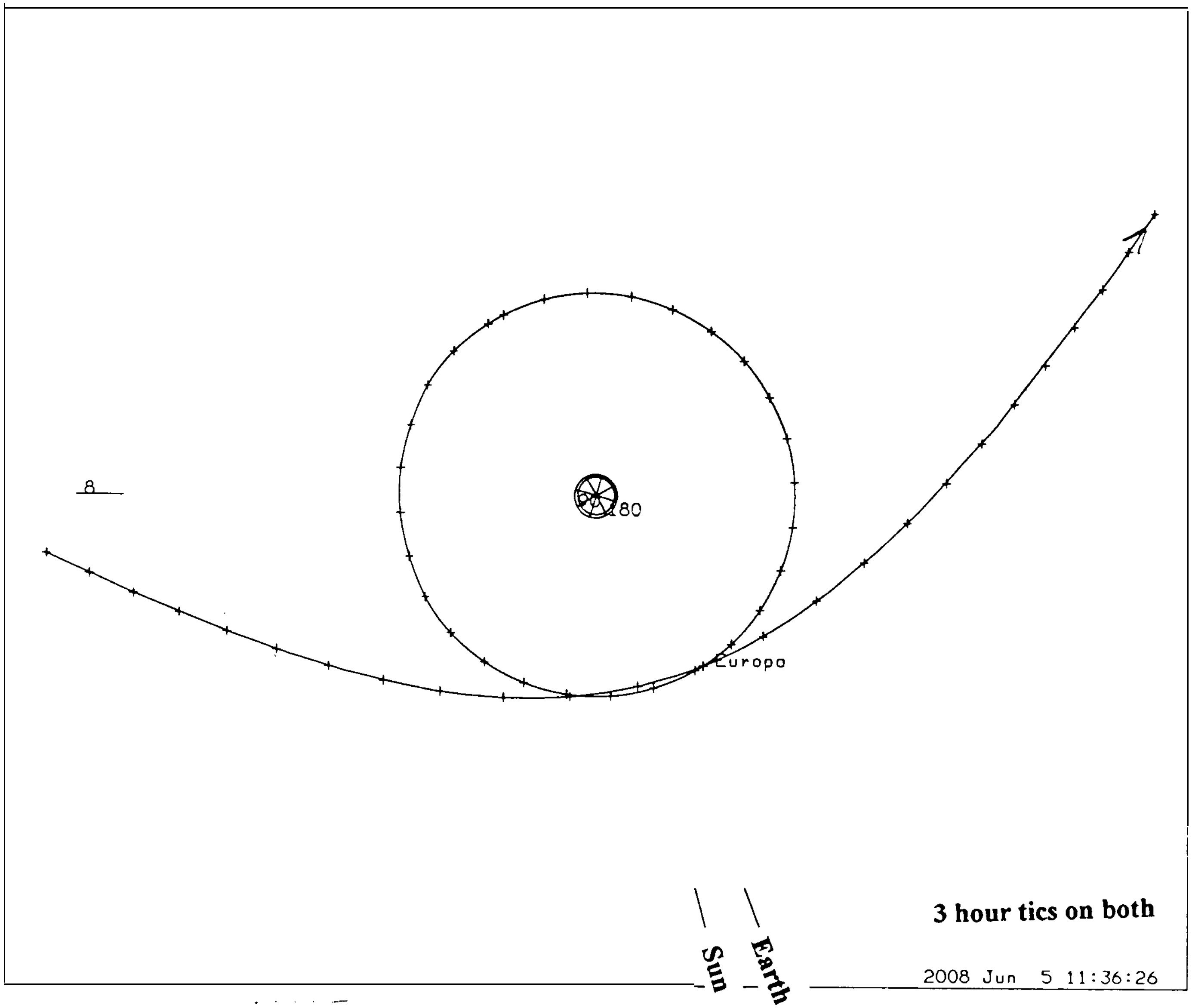

Figure 6 Jupiter-Europa Flyby, 2000 Launch

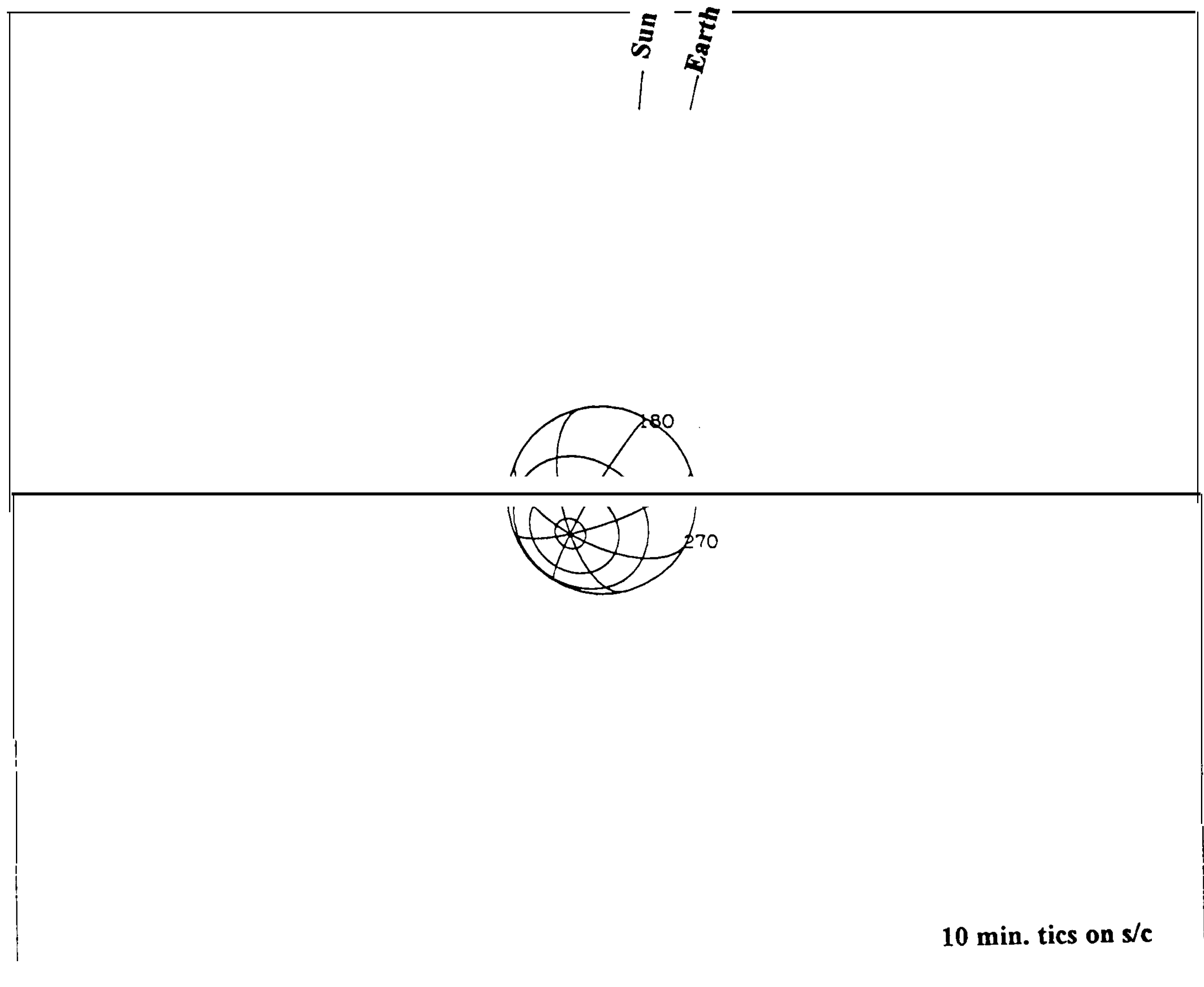

Figure 7 Europa Flyby, 2000 Launch, 60 Degrees South

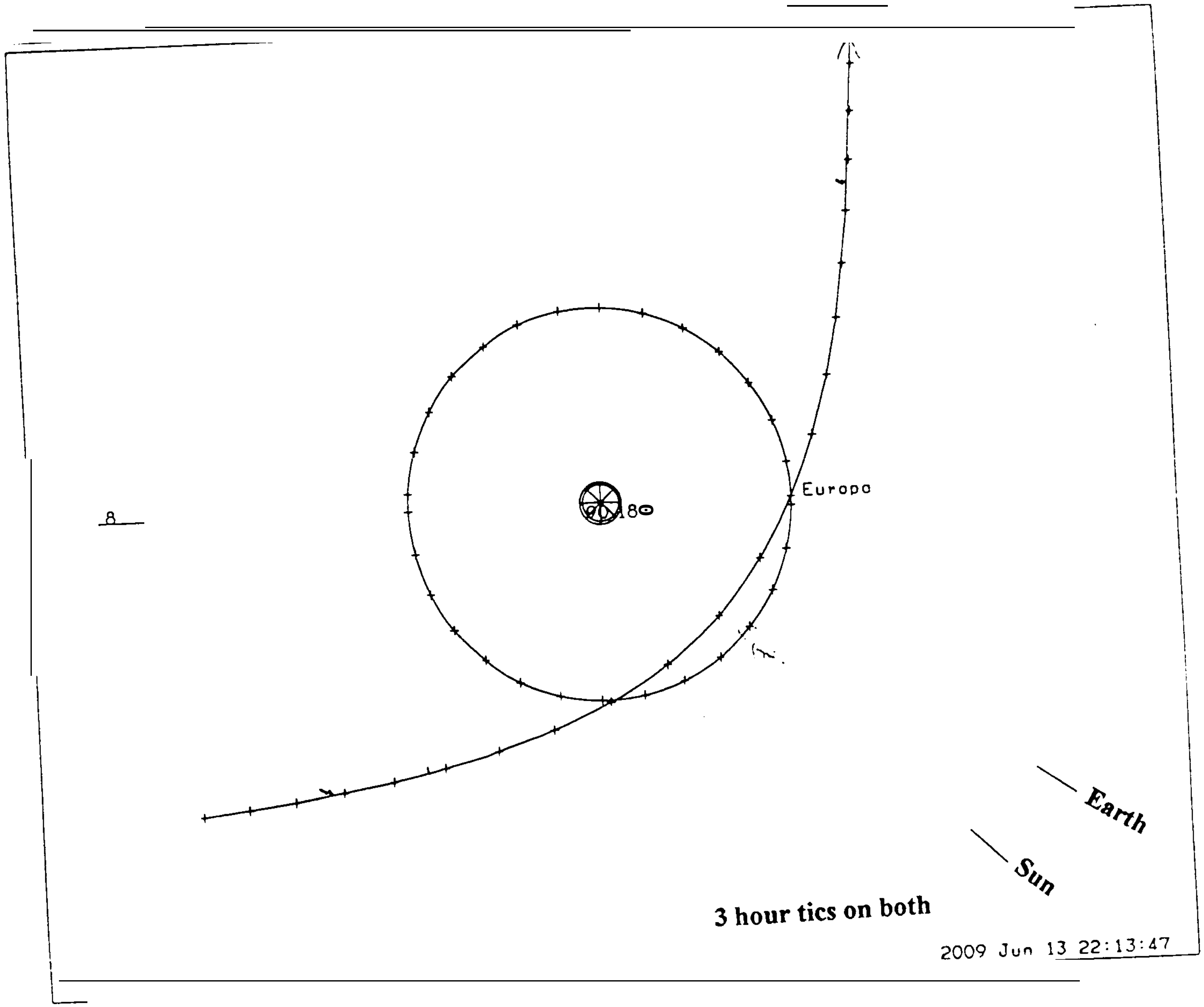

Figure 8 Jupiter-Europa Flyby, 2001 Launch

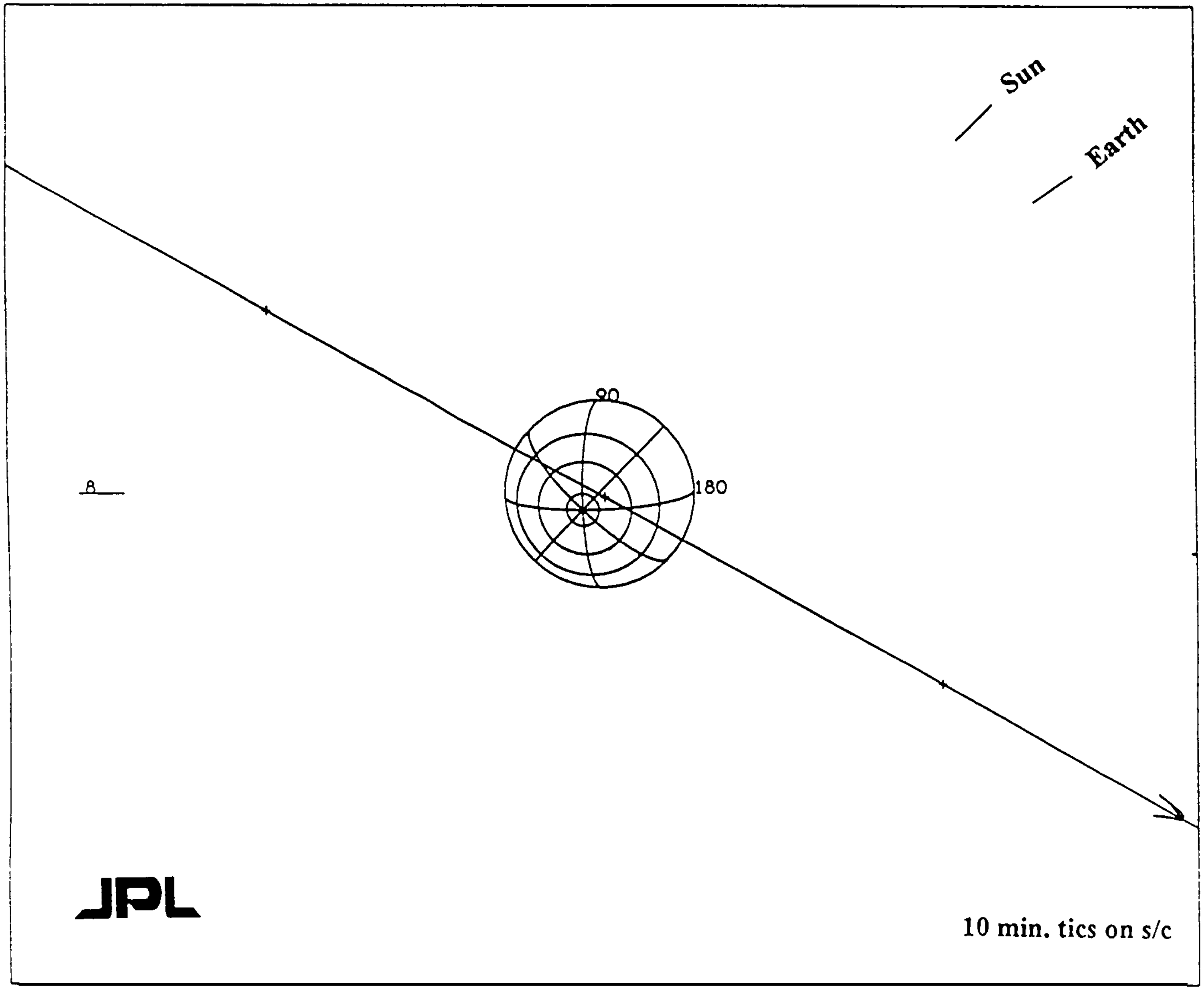

Figure 9 Europa Flyby, 200 Launch, 75 Degrees South

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Figure 10 LOCI OF SUB PERIAPSE POINTS ON EUROPA
With Trajectory Headings

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Figure 10 Loci of Sub-Periapse Points on Europa

THE EUROPA FLYBY

The scenario at Europa to be attempted in the ICE-CLIPPER mission is to launch a dense solid probe to strike the icy surface of Europa just before the spacecraft arrives. It is intended that the spacecraft will sweep through the debris ejected into the space above the surface. The desired approach speed of the probe is from 8 to 10 km/s with expectation that it will cause the ejection of vapors and molecules so as to fill a hemisphere about a thousand kilometers in radius in about one hundred seconds,. The spacecraft was to fly through the cloud and collect its sample in jell similar to the technique being used on the Stardust mission, The probe is to be aimed to strike the surface a few hundred kilometers before the Europa periapse which is planned to be at the altitude of 50 km. The Europa flyby speed of the spacecraft and that of the probe as well is not an open parameter, but fortunately the flyby speeds for some trajectories do closely satisfy this 10 km/see limitation, One of the consequences of the close Europa flyby is that it introduces a bend of about 5 degrees in the Jupiter centered trajectory and this must be included in obtaining the total bend in the Jupiter system for the return flight to Earth. The target plane angle at Europa is, *on* the other hand, a free variable. It determines the location of the point of closest approach on Europa, the heading of the spacecraft over it, and the plane in which the 5 degree bend takes place. Varying it over the whole 360 degree range changes the delta-V needed near Jupiter for the Earth return to vary over a range of about 500 m/see.. The minimum value of this impulse can be zero, but in any case the minimum value corresponds to a particular periapse point and flyby direction on Europa. Moving this point to same different and more desirable location always requires an increase in the total post launch delta-V

It is clear from the symmetry of these trajectories that the perijove point will be very near the Sun-Jupiter line. The Europa encounter will also be near this line although if the perijove distance is below the Europa distance the encounter can be on either before or after the perijove. For trajectories leaving the Earth in 2001 the perijove is just outside the Europa distance and the flyby on the dark side of Europa(the side facing Jupiter) supplies just the right extra amount of bending to yield the Earth return trajectory for a certain target angle. Thus a lighted side flyby in this case will cost some delta-V as explained above. As seen from Table 4 or from Figure 4, the trajectories that leave the Earth from 2002 to 2008 have perijove distance under the Europa distances. Impulses of several tens of meters per second can also move the Europa periapse along the Jupiter centered trajectory distance a small amount, For all of these trajectories tested (2002-2005) the minimum impulse has always accompanied the highest positive value of the true anomaly in the Jupiter centered orbit at the Europa encounter.

LAUNCH AND SPACECRAFT CONSIDERATIONS

In Table 4 it is seen that the launch energies for the direct Europa mission are at least 86 km^2/sec^2. In order to allow to allow for a ten day launch window it is necessary to provide for a C3 up to 90 km^2/sec^2. The largest launch system that we may consider for this mission is the Delta 11(7925) and the mass that could be launched is slightly over 200 kg. This is considered inadequate to carry out all the operations involved in the ICE-CLIPPER mission, Thus it is necessary to turn to an Earth gravity assist to provide enough mass even though it requires an extra two years of flight time and nearly 800 m/sec of delta-V. Table 6 contains a summary of the launch and trajectory possibilities for flights utilizing the 2002, the 2003-4, and the 2005 ten-year Earth-Jupiter-Earth trajectories. The first line for each launch year is for the trajectory at Europa requiring the least post launch delta-V. The sub satellite point is very near the south pole of Europa, It is moved by five or ten degree increments in the target plane angle toward lighted side. If the Europa encounter is at perijove the Sun will be shining down on longitude 180 degrees. and as the true anomaly in the Jupiter centered system increases the Sun moves the same amount to lower (east)longitudes, that is toward the west as on the Earth. In Table 6 the launch requirements are given, also all the deterministic post launch delta-V's, the periapse point on Europa (latitude and east longitude), the relative velocity and its heading (azimuth), the true anomaly on the Jupiter centered trajectory at periapse, and the Earth return approach speed.

For trajectories that leave the Earth in 2003-4 and 2005 the perijove distance is so much *lower* than the orbit of Europa that the Europa flyby speed is well above 10 km/s, which was taken an upper limit for a satisfactory ICE-CLIPPER Europa flyby speed. They are included in this discussion and shown in the final table (Table **6)** of possible trajectories to illustrate this condition, But we have to add that the next opportunity for an Europa trajectory for an ICE-CLIPPER mission would make use of the 2009 Earth departure(see Figure 4). The back up trajectories for ICE-CLIPPER can only be the direct launches in 2001 and 2002 provided that a more capable launch systems is used or a smaller spacecraft could be developed in time

Finally Figure 5 is an ecliptic plane projection of the whole ICE-CLIPPER trajectory. The spacecraft would be launched in November 2000 and make use of 2002 Earth-Jupiter-Earth ten-year trajectory. Figures 6 and 7 illustrate the Europa encounter for the target plane angle case of 60 degrees in a Jupiter centered diagram and a Europa centered diagram respectively. Figures 8 and 9 are similar trajectory plots for the 2003 launch with the target plane angle at 75 degrees. In Figures 6 and 8 the directions to the Sun and to the Earth are shown. In Figures 7 and 9 the view is of Europa's South Pole and the latitude circles shown are for 40, 60, and 80 degrees south. Figure 10 shows the loci of the periapse points on the surface of Europa for the three series of trajectories in Table 8. The map is a portion of the USGS map of Europa produced in 1971. Short arrows are drawn to indicate the direction (azimuth) of the motion of the spacecraft over the surface at periapse. The perijove point on the Jupiter centered trajectory lies in the direction of the Sun from Jupiter because of the over symmetry of these trajectories in the Solar system, Since Europa rotates synchronously with its orbital motion around Jupiter the true anomaly given in the next to last column in **Table** 6 is also the angle in longitude the sun has moved from 180 degrees longitude (to lower longitudes) on Europa. This map can not contain the south polar region where the lowest post launch delta-V cases occur, but it does show the accessible region of most interest and that it will be illuminated as the spacecraft flies by...